NEUTRINOLESS DOUBLE BETA DECAY: SEARCHING FOR NEW PHYSICS WITH COMPARISON OF DIFFERENT NUCLEI

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Abstract. The neutrinoless double beta decay is analyzed using a general Lorentz invariant effective Lagrangian for various decaying nuclei of current experimental interest: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, and ^{136}Xe. We work out the half-lives and angular correlation coefficients of the outgoing electrons in several scenarios for new physics: the left-right symmetric models, the R-parity-violating SUSY and models with leptoquarks. The theoretical uncertainty in the nuclear matrix elements is discussed.

1. The Majorana nature of neutrino masses is anticipated by most of the theories created to explain the observable lightness of neutrinos, in particular, seesaw mechanism and models with radiative neutrino mass generation (see [1, 2] and references therein). Experimental evidence for the neutrinoless double beta decay ($0\nu2\beta$) would deliver a conclusive confirmation of the Majorana nature of neutrinos, in contrast to the Dirac nature of all other known fermions. This is the overriding interest in carrying out these experiments and in the related phenomenology [3]. We recall that $0\nu2\beta$ decays are forbidden in the Standard Model (SM) by lepton number (LN) conservation. However, an extended version of the SM could contain terms that violate LN and allow the $0\nu2\beta$ decay. Probable mechanisms of LN violation may include exchanges by: Majorana neutrinos ν_Ms, SUSY Majorana particles, scalar bilinears , e.g. doubly charged Higgs, leptoquarks, right-handed W_R bosons etc. [1]. These various contributions will have to be disentangled to extract information from the $0\nu2\beta$ decay on the characteristics of the sources of LN violation, in particular, on the neutrino masses and mixing. Measurements of the $0\nu2\beta$ decay in different nuclei will help to determine the underlying physics mechanism [4–6]. In Ref. [7] the $0\nu2\beta$ decay angular correlation for the ^{76}Ge nucleus was investigated in order to discriminate among the various possible mechanisms contributing to this decay. However much more new physics one can extract using the experimental data for various decaying nuclei. In this report, we generalize the analysis of Ref. [7] for the case of the following set of nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, and ^{136}Xe.

2. Following Ref. [7], we use the general effective Lagrangian for the $0\nu2\beta$ decay

$$\mathcal{L} = \frac{G_{\mathrm{F}} V_{ud}}{\sqrt{2}} [(U_{ei} + \epsilon^{V-A}_{V-A,i}) j^{\mu i}_{V-A} J^{+}_{V-A,\mu} + {\sum_{\alpha,\beta}}' \epsilon^{\beta}_{\alpha i} j^{i}_{\beta} J^{+}_{\alpha} + \mathrm{H.c.}] \,, \tag{1}$$

where the hadronic and leptonic currents are defined as: $J^{+}_{\alpha} = \bar{u} O_{\alpha} d$ and $j^{i}_{\beta} = \bar{e} O_{\beta} \nu_i$; the leptonic currents contain neutrino mass eigenstates and the

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index i runs over the light eigenstates; a summation over the repeated indices is assumed; $\alpha, \beta{=}V\mp A, S\mp P, T_{L,R}$ ($O_{T_\rho} = 2\sigma^{\mu\nu}P_\rho$, $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, $P_\rho = (1\mp\gamma_5)/2$ is the projector, $\rho = L, R$); the prime indicates the summation over all the Lorentz invariant contributions, except for $\alpha = \beta = V - A$, U_{ei} is the PMNS mixing matrix [8] and V_{ud} is the CKM matrix element [9]. The coefficients $\epsilon^{\beta}_{\alpha i}$ encode new physics, parametrizing deviations of the Lagrangian from the standard $V - A$ current-current form and mixing of the non-SM neutrinos. Eq. (1) describes the so-called long range mechanism of the $0\nu2\beta$ decay mediated by light Majorana neutrinos.

The differential width for the $0^+(A,Z) \to 0^+(A,Z+2)e^-e^-$ transitions is [7]

$$d\Gamma/d\cos\theta = (\ln 2/2)|M_{\rm GT}|^2\mathcal{A}(1 - K\cos\theta), \quad K = \mathcal{B}/\mathcal{A}\ , \ -1 < K < 1, \tag{2}$$

where θ is the angle between the electron momenta in the rest frame of the parent nucleus, $M_{\rm GT}$ is the Gamow–Teller nuclear matrix element, and K is the angular correlation coefficient. Eq. (2) is derived taking into account the leading contribution of the parameters $\epsilon^{\beta}_{\alpha} = U_{ei}\epsilon^{\beta}_{\alpha i}$. The expressions for $\mathcal{A}$ and $\mathcal{B}$ for different choices of $\epsilon^{\beta}_{\alpha}$, with only one nonzero coefficient considered at a time, are given in Ref. [7].

Using the data on various decaying nuclei we have considered the two particular cases for the parameter space: A) $\epsilon^{\beta}_{\alpha} = 0$, $|\langle m\rangle| \neq 0$ (SM plus Majorana neutrinos), B) $\epsilon^{\beta}_{\alpha} \neq 0$, $|\langle m\rangle| = 0$ (vanishing effective Majorana mass). Only the terms with $\epsilon^{V\mp A}_{V\mp A}$ are taken into account as the corresponding nuclear matrix elements have been worked out in the literature [10].

The differences in the half-lives and angular coefficients for various nuclei are described by the ratios $\mathcal{R}^{\beta}_{\alpha}(^A{\rm X}) = T_{1/2}(\epsilon^{\beta}_{\alpha}, ^A{\rm X})/T_{1/2}(\epsilon^{\beta}_{\alpha}, ^{76}{\rm Ge})$ and $\mathcal{K}^{\beta}_{\alpha}(^A{\rm X}) = K(\epsilon^{\beta}_{\alpha}, ^A{\rm X})/K(\epsilon^{\beta}_{\alpha}, ^{76}{\rm Ge})$, for the choice of only one nonzero coefficient $\epsilon^{\beta}_{\alpha}$ which characterize specific alternative new physics contributions (we make a comparison with ^{76}Ge as it is the best tested isotope to date). The numerical values of $\mathcal{R}$, $\mathcal{K}$ and $\mathcal{R}^{\beta}_{\alpha}$, $\mathcal{K}^{\beta}_{\alpha}$ corresponding to cases A) and B), respectively, are given in Tables 1 and 2 for two different nuclear models: QRPA without and with p-n pairing [10].

Table 1: The ratios of the half-lives $\mathcal{R}$ and $\mathcal{R}^{\beta}_{\alpha}$ for various nuclei in QRPA without (with) p-n pairing [10].

Nucleus	$\mathcal{R}{=}\mathcal{R}^{V-A}_{V-A}$	$\mathcal{R}^{V-A}_{V+A}$	$\mathcal{R}^{V+A}_{V-A}$	$\mathcal{R}^{V+A}_{V+A}$
^{82}Se	0.42 (0.15)	0.37 (2.76)	2.10 (3.07)	0.24 (0.03)
^{100}Mo	1.08 (195.18)	52.87 (0.59)	1.11 (0.49)	1.06 (0.79)
^{130}Te	0.24 (0.11)	0.21 (0.16)	0.20 (0.12)	0.15 (0.03)
^{136}Xe	0.53 (0.15)	0.40 (0.37)	0.41 (0.22)	0.34 (0.06)

The entries for the ratios of the half-lifes are well separated, besides the $\mathcal{R}^{V-A}_{V-A}$, which is equal to $\mathcal{R}$. However, they are dominated by the uncertainties of the nuclear model. On the other hand, the angular coefficients $\mathcal{K}$ and $\mathcal{K}^{V-A}_{V\pm A}$ do not depend on the nuclear matrix elements, and coefficients $\mathcal{K}^{V+A}_{V-A}$ essentially do not depend on the uncertainties of the nuclear model. Moreover, the ratios of the angular correlations are not discriminating among the

Table 2: The ratios of the angular coefficients $\mathcal{K}$ and $\mathcal{K}_\alpha^\beta$ for various nuclei in QRPA without (with) p-n pairing [10].

Nucleus	$\mathcal{K}$=$\mathcal{K}_{V\pm A}^{V-A}$	$\mathcal{K}_{V-A}^{V+A}$	$\mathcal{K}_{V+A}^{V+A}$
^{82}Se	1.08	1.11 (1.11)	1.13 (0.95)
^{100}Mo	1.08	1.14 (1.14)	1.13 (0.84)
^{130}Te	1.04	1.07 (1.07)	1.01 (0.90)
^{136}Xe	1.03	1.06 (1.06)	0.98 (0.91)

various underlying theories as within the anticipated experimental uncertainty they are all consistent with unity. The most sensitive to the listed ratios is ^{100}Mo, except for the ratio $\mathcal{R}_{V-A}^{V+A}$ to which the most sensitive is ^{82}Se. From the measurements of the half-lives, the most sensitive to the effects of $\epsilon_{V+A}^{V\pm A}$ and ϵ_{V-A}^{V+A} are the pairs ^{100}Mo – ^{130}Te and ^{82}Se – ^{130}Te, correspondingly. From the measurements of the angular coefficients, the most sensitive to the effects of $\epsilon_{V\pm A}^{V+A}$ is the pair ^{76}Ge – ^{100}Mo.

3. In conclusion, the comparison of the half-lives and the electron angular correlations for the selected decaying nuclei would help to minimize the theoretical uncertainties in the nuclear matrix elements and identify the dominant mechanism underlying these decays. At present, no experiment is geared to measuring the angular correlations in $0\nu2\beta$ decays, as the main experimental thrust is on establishing a nonzero signal unambiguously in the first place. The running experiment NEMO3 has already measured the electron angular distributions for the two neutrino double beta decays of ^{100}Mo and ^{82}Se, and is capable of measuring these correlations in the future for the $0\nu2\beta$ decays as well, assuming that the experimental sensitivity is sufficiently good to establish these decays [11]. The proposed experimental facilities that can measure the electron angular correlations in the $0\nu2\beta$ decays are SuperNEMO [12], MOON [13], and EXO [14].

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